



The realities of storing carbon dioxide

A response to CO₂ storage capacity issues
raised by Ehlig-Economides & Economides



Contents

1 Introduction	3
2 Open vs. closed CO₂ storage reservoirs	3
2.1 Closed reservoirs	3
2.2 Open reservoirs	3
3 CO₂ storage capacity	4
4 Pressure management	4
5 CO₂ storage integrity	5
6 CO₂ dissolution in storage reservoirs	5
7 CO₂ storage in depleted reservoirs	5
8 Calculations and inconsistencies	6
8.1 Scenario 1	7
8.2 Scenario 2	7
9 Conclusions	8
10 Contributors	8
11 References	9

1 Introduction

In a recent publication, Ehlig-Economides & Economides (2010) have sought to demonstrate that carbon dioxide capture and storage (CCS) is not technically or economically feasible, based on a supposed lack of underground storage capacity. **We consider this to be a serious misrepresentation of the scientific, engineering and operational facts surrounding CCS.**

Ehlig-Economides & Economides, referred to hereafter as E&E, raise a number of storage related issues: reservoir boundaries, capacity, pressure management, storage integrity, dissolution and storage in depleted reservoirs. We take each one in turn below, highlighting specific errors in the paper but also drawing attention to more general background issues. Finally, we discuss in more detail some inconsistencies in the paper surrounding the reservoir engineering calculations.

2 Open vs. closed CO₂ storage reservoirs

Fundamental to E&E's argument is the statement that storage reservoirs must behave as closed containers - subsurface vessels with impermeable boundaries on all sides, into which fluid is injected and total injection volume is limited by the properties of the vessel itself. This system definition places an intrinsic limit on total storage capacity due to the necessity of controlling underground pressure increase within the closed containers.

2.1 Closed reservoirs

The closed container forms a hypothetical end-member of a whole spectrum of reservoirs with a range of boundary conditions. In fact, without exception, sedimentary formations, reservoirs or otherwise, are surrounded by rocks which are variably porous and permeable. A suitable storage reservoir will necessarily be overlain by a capillary seal to prevent the escape of buoyant CO₂. This seal may or may not allow expulsion of water on relevant timescales. There is no requirement for the reservoir to be sealed below, either operationally or geologically.

2.2 Open reservoirs

Reservoirs are also commonly open at their margins, so single phase flow, laterally or vertically, can allow water to escape without any detrimental effect on storage integrity for CO₂. Evidence for water flow within and across the boundaries of reservoirs (on spatial scales orders of magnitude larger than the containers proposed by E&E), comes from a century of oil production (oil companies actually produce more water than oil) and from the water resources industry.

Many of these aquifers are of huge extent, for example the Utsira Sand and similar reservoirs in the North Sea. In Oman the Haima aquifer is charged by mountain water in the north which flows, through the aquifer, many hundreds of kilometres to south. The inclined water-oil contacts observed in many oil fields are also indicative of regional hydraulic connectivity. In fact, for potable aquifers, without this scale of water flow, groundwater-based drinking water resources could not work.

3 CO₂ storage capacity

Limiting the argument to the USA, E&E state that required reductions from present day emissions need to be around 1.75 billion tonnes of CO₂ per year until 2030, for an ultimate stored mass of 52.5 billion tonnes.

In its 2008 Carbon Sequestration Atlas, NETL estimated that at 1% storage efficiency, the saline aquifer storage potential of the US is 3,296 billion tonnes, far in excess of the requirement. A more conservative calculation using a storage efficiency of 0.05%, which is comparable to the efficiency of E&E's hypothetical reservoir, still gives a total capacity of 165 billion tonnes – more than double the requirement. The conclusion of E&E that capacity has been overestimated to the extent that CCS is unfeasible is therefore inaccurate. Given the impact of E&E's conclusions regarding capacity, it is important to assess whether the underlying assumptions represent a realistic or typical storage scenario.

In our view their case is not representative of the overwhelming majority of storage opportunities that would be encountered in the large, regional reservoirs likely to serve as “baseload” storage capacity, either in the United States or elsewhere (Dahowski et al. 2005, 2010; Nicot 2008). In addition, E&E's radical extrapolation of the results from a single reservoir to a commentary on regional storage capacity is virtually meaningless as it supposes that just one (very thin) reservoir would be available for storage in the entire geological column.

4 Pressure management

The need for effective pressure management is well understood. The injectivity of CO₂ into both open and closed aquifers has been discussed by a number of authors (e.g Mathias et al., 2009a; Mathias et al., 2009b; van der Meer and Egberts, 2008; Zhou et al., 2007). These studies examined the potential limiting role that injectivity might play, calling for careful storage characterization including well testing prior to qualifying the site, but none have suggested that CO₂ storage is “not a practical means to provide any substantive reduction in CO₂ emissions”.

E&E seek to use observations from Sleipner, the world's largest and longest-running aquifer storage project, to support their views. Their specific statement regarding Sleipner as ‘seeming to warn of problems’ wilfully misrepresents the findings of Bickle et al. (2004) and disregards numerous other peer-reviewed publications. In fact, development and migration of the CO₂ plume at Sleipner is very much as predicted, with no migration from the storage reservoir so far detected and no leakage. Simulated pressure increase is negligible and this is supported by the measurements (Chadwick et al. 2009). For the record, Sleipner has now injected 12 million tonnes of CO₂ at a rate of about 1 million tonnes per year. This represents just three one thousandths of one percent of the reservoir pore-volume.

5 CO₂ storage integrity

E&E's statement that an open or outcropping aquifer is unsuitable for CO₂ storage because it will lead to the release of CO₂ back to the atmosphere is self-evidently untrue for aquifers with structural closures and is contradicted by a substantial body of literature. It disregards a whole range of reservoir processes related to residual trapping and dissolution. These processes act in the medium-term to retard the movement of, and eventually immobilize, CO₂ in the storage formation, ultimately reversing density-driven buoyant flow to allow denser CO₂-saturated water to sink in the reservoir (Benson 2008; Hovorka et al., 2006). This allows for the definition of a finite boundary to the extent of CO₂ migration during storage, contradicting E&E's supposition that injected CO₂ will simply migrate forever until it finds a migration pathway out of the storage formation and into the atmosphere.

6 CO₂ dissolution in storage reservoirs

E&E dismiss dissolution, saying it is a "woefully slow process", and neglect it in their calculations. Although substantial CO₂ dissolution is not immediate and its rate is not yet well calibrated, one must be careful in denying its benefits. Indeed, in a porous medium for time and spatial scales involved in CCS (several tens of years, several km² impacted by free CO₂), dissolution will generally occur to a significant extent before the end of operation (e.g. Ennis-King and Paterson 2007).

7 CO₂ storage in depleted reservoirs

E&E suggest that aquifer storage is the sole determinant of CCS viability, specifically dismissing depleted gas reservoirs as CO₂ storage prospects " [...] typically such reservoirs are used for natural gas storage and would not be available for carbon dioxide sequestration."

Certainly from a European perspective this is untrue. It is the larger depleted gas fields which are currently envisaged for CO₂ storage. These are too large for cost-effective natural gas storage, due to their excessive cushion gas requirement, so competition between CCS and natural gas storage is minimal.

With regard to the more general storage potential of depleted hydrocarbons fields, Lovell (2010) quotes some striking figures: "The volumes of carbon dioxide required to make a dent in the Princeton targets are huge.

Schiermeier (2006, p. 621) gives some figures: Locking away 250 million tonnes of carbon [915 million tonnes of carbon dioxide] per year – equivalent to 4% of annual global emissions – would require an injection of 25 million to 35 million barrels [of carbon dioxide] per day, depending on compression density. That's equivalent to about a third of the flow of oil per day currently coming from reservoirs.

These volumes have to be set against the original (Pacala and Socolow, 2004) Princeton calculations, according to which we have to find a way not to release 175 gigatonnes of carbon (equivalent to 640 gigatonnes of carbon dioxide) over the next 50 years. Yet there is some consolation to be found in the oilfields themselves.

The term 'oil industry' is in one sense misleading: the major product is salty water pumped to the surface with the oil. (Oil-bearing rocks also contain original water in their pores which is produced with the oil; oil reservoirs produce more and more water as the oil is pumped out, to be replaced in the pores by inflowing water.) Daily oil production of over 80 million barrels is accompanied by well over 200 million barrels of water (Veil, Puder, Elcock and Redwell, 2004). Reversing that total flow of some 300 million barrels a day, by

injecting into existing reservoirs (say) 2,500 million tonnes of carbon a year, in the form of over 9,000 million tonnes of carbon dioxide, would cope with 125 gigatonnes of carbon (450 gigatonnes of carbon dioxide), about 70% of the 2004 Princeton target for controlling emissions through to the middle of the twenty-first century. That is not going to happen, but it does give some indication of the scale of the contribution that could be made by the use of the existing oil reservoirs.”

8 Calculations and inconsistencies

In addition to the more generic issues raised above, closer examination shows that E&E's conclusions are inconsistent with their own reservoir engineering calculations.

The final paragraph of Section 2 (page 126) states: “Of course, greater aquifer thickness reduces the required aquifer area by increasing both injectivity and storability per unit area. If an otherwise similar aquifer is 200 ft thick instead of 100 ft, the area required with 1000 psi pressurisation is reduced to 686 sq mi, and 2 wells, each requiring a square area approximately 17.5 mi on a side, are sufficient.”

Assumptions about the aquifer quoted in the paper include:

Area	686 square miles
Thickness	200 ft
Porosity	20%
Permeability	100 mD
Depth	6000 ft
Temperature	150 F
Initial Pressure	2598 psi
Acceptable pressure increase	1000 psi
Irreducible water saturation	0.558
Endpoint CO ₂ relative permeability	0.32

E&E state that this system can be used for injection and storage of 3 MT/yr for 30 years (equivalent to the output from a 500 MW coal fired powered station) via two wells, without inducing a pressure increase in excess of 1,000 psi. Thus, according to the figures quoted, the power station would require two closed aquifers, each of areal extent similar to Prudhoe Bay (which is 337 square miles) and thickness of 200 ft, with just one injection well in each.

This is at odds with the final statement of the paper: “Conversely, for more moderate size reservoirs, still the size of Alaska’s Prudhoe Bay reservoir, and with moderate permeability, there would be a need for hundreds of wells [...] the findings of this work clearly suggest that it is not a practical means to provide any substantive reduction in CO₂ emissions, although it has been repeatedly presented as such by others.”

It is difficult to see how credence is gained for this final statement, which directly contradicts the earlier calculation.

E&E also present two scenarios which give rise to misleading conclusions.

8.1 Scenario 1

Injection into an aquifer with the above properties, but with thickness of 100 ft and with an allowable pressure increase of only 100 psi. The reason given by E&E for limiting pressure increase to this very low value is that injected gas can never be fully recovered. But this is not a requirement of CO₂ storage, so the 100 psi pressure limit is completely unnecessary. Although only two wells are required in this case, the other assumptions increase the required reservoir area from 686 square miles to 13,800 square miles. The paper very quickly drops the 100 psi pressure criterion, but not before making the irrelevant assertion that nine US states have areas less than this.

8.2 Scenario 2

Injection into an aquifer with the above properties, but with a thickness reduced to 100 ft, and an allowable pressure increase of 1,600 psi. An aquifer area of 853 square miles would now be required, but within this restricted volume pressure build-up around the CO₂ injection wells has to be limited. E&E suggests that 1,155 wells would be needed to avoid excessive pressure increase. Of course, this assumes simple 100 ft vertical completions. Faced with such a scenario, the practical choice would be to drill a far smaller number of horizontal wells, or to drill water production wells to reduce reservoir pressure and allow for greater injection from a much smaller well stock.

9 Conclusions

E&E assert that “underground carbon dioxide sequestration via bulk CO₂ injection is not feasible at any cost.” This is inconsistent with the experience gained from a number of varied CO₂ injection projects around the world and countless other fluid injection projects over the last several decades such as the injection of hundreds of billions of gallons of waste fluid into the subsurface under the auspices of the U.S. EPA Underground Injection Control Program (EPA, 2002). Not only are these projects technically and economically viable, they are effectively managed and safely regulated.

E&E’s central premise is that CO₂ storage requires a closed storage container, sealed on all sides by impermeable boundaries, to prevent leakage. This is demonstrably untrue.

Moreover, even within the bounds of their own analysis, E&E have had to conflate carefully selected reservoir parameters into improbable storage scenarios to make their case. Should a real storage project wish to utilise closed target reservoirs, the volume balance would be assessed on an individual basis to match capacity with powerplant emissions. This would then be linked to an assessment of storage integrity, injectivity and any requirements for pressure control, such as water extraction. This type of engineering, already well mastered by the oil and gas industry, does precisely what the E&E calculations do not allow: it distributes the excess fluid over subsurface volumes much larger than the storage reservoir itself.

E&E’s paper therefore is built upon one main premise, without which the paper falls. It is notable that even with the premise, E&E struggle to deliver their central thesis. Their own calculations, when applied to credible storage scenarios with reasonable reservoir properties, do not support it.

10 Contributors

Andy Chadwick, Dan Smith (British Geological Survey, UK)
Chris Hodrien (UK)
Sue Hovorka (University of Texas at Austin, US)
Eric Mackay (Heriot-Watt University, UK)
Simon Mathias (Durham University, UK)
Bryan Lovell (University of Cambridge, UK)
Francois Kalaydjian (IFP, France)
Graeme Sweeney (Shell, UK)
Sally Benson (Stanford University, US)
Jim Dooley, Casie Davidson (Pacific Northwest National Laboratory, US)

The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) – otherwise known as the Zero Emissions Platform – is a broad coalition of stakeholders united in their support for CCS and its leading authority in Europe. Members include European utilities, petroleum companies, equipment suppliers, national geological surveys, academic institutions and environmental NGOs.

For more information, please visit: www.zeroemissionsplatform.eu

11 References

- Benson SM, 2008. Multi-Phase Flow and Trapping of CO₂ in Saline Aquifers. (Paper No. OTC 19244). Published in the Proceedings of 2008 Offshore Technology Conference held in Houston, TX, USA, May 5–8, 2008.
- Bickle, M., Chadwick, R.A., Huppert, H.E., Hallworth, M. & Lyle, S. 2007. Modelling Carbon-Dioxide Accumulation at Sleipner: Implications for Underground Carbon Storage. *Earth & Planetary Science Letters*, 255, 164 – 176.
- Chadwick, R.A., Noy, D.J. & Holloway, S. 2009. Flow processes and pressure evolution in aquifers during the injection of supercritical CO₂ as a greenhouse gas mitigation measure. *Petroleum Geoscience*, 15, 59-73.
- Dahowski, R.T., Dooley, J.J., Davidson, C.L., Bachu, S. & Gupta, N. 2005. Building the Cost Curves for CO₂ Storage: North America. Technical Report 2005/3. International Energy Agency Greenhouse Gas R&D Programme.
- Dahowski, R.T., Li, X., Davidson, C.L., Wei, N. & Dooley, J.J. 2010. Regional Opportunities for Carbon Dioxide Capture and Storage in China: A Comprehensive CO₂ Storage Cost Curve and Analysis of the Potential for Large Scale Carbon Dioxide Capture and Storage in the People's Republic of China . PNNL-19091, Pacific Northwest National Laboratory, Richland, WA.
- Ehlig-Economides, C.A. & Economides, M.J. 2010. Sequestering carbon dioxide in a closed underground volume, *Journal of Petroleum Science and Engineering*, 70, 123-130.
- Ennis-King, J. & Paterson, L. 2007. Coupling of geochemical reactions and convective mixing in the long-term geological storage of carbon dioxide, *International Journal of Greenhouse Gas Control*, 1, 86-93.
- EPA. 2002. "Protecting Drinking Water through Underground Injection Control: Drinking Water Pocket Guide #2." http://www.epa.gov/safewater/uic/pdfs/pocketguide_uic_protectng_dw_thru_uic.pdf
- Hovorka S.D., Benson, S.M., Doughty, C. Freifeld, B.M., Sakurai, S., Daley, T.M., Kharaka, Y.K., Holtz, M.H., Trautz, R.C., Seay Nance, H., Myer, L.R. & Knauss, K.G. 2006. Measuring permanence of CO₂ storage in saline formations: the Frio experiment. *Environ. Geosci.* 13 (June (2)), 105–121, doi:10.1306/eg.11210505011.
- Lovell, B. 2010. Challenged by Carbon: The Oil Industry and Climate Change. Cambridge University Press. 212pp.
- Mathias, S.A., Hardisty, P., Trudell, M. & Zimmerman, R., 2009a, Approximate Solutions for Pressure Buildup During CO₂ Injection in Brine Aquifers: Transport in Porous Media, v. 79, p. 265-284.
- Mathias, S.A., Hardisty, P.E., Trudell, M.R. & Zimmerman, R.W. 2009b, Screening and selection of sites for CO₂ sequestration based on pressure buildup: *International Journal of Greenhouse Gas Control*, v. 3, p. 577-585.
- Nicot, J.-P. 2008, Evaluation of large-scale CO₂ storage on fresh-water sections of aquifers: An example from the Texas Gulf Coast Basin: *International Journal of Greenhouse Gas Control*, v. 2, p. 582-593.
- Pacala, S. & Socolow, R. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, 305, 968–972.
- Schiermeier, Q. 2006. Putting the carbon back: the hundred billion tonne challenge. *Nature*, 442, 620–623.
- van der Meer, L.G.H. & Egberts, P.J.P., 2008. A general method for calculating subsurface CO₂ storage capacity, Offshore Technology Conference: Houston, Texas, USA.
- Veil, J. A., Puder, M. G., Elcock, D. & Redwell Jr, R. J. 2004. A White Paper describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane, prepared by Argonne National Laboratory for US Dept of Energy, National Energy Technology Laboratory, under contract W-31–109-Eng-38.
- Zhou, Q., Birkholzer, J.T., Rutqvist, J. & Tsang, C.-F. 2007. Sensitivity study of CO₂ storage capacity in brine aquifers with closed boundaries: dependence on hydrogeologic properties, Sixth Annual Conference of Carbon Capture and Sequestration: Pittsburgh, PA, USA.

For further information, please contact:

Eric Drosin

Director of Communications

Zero Emissions Platform (ZEP)

Email: edrosin@zero-emissionplatform.eu